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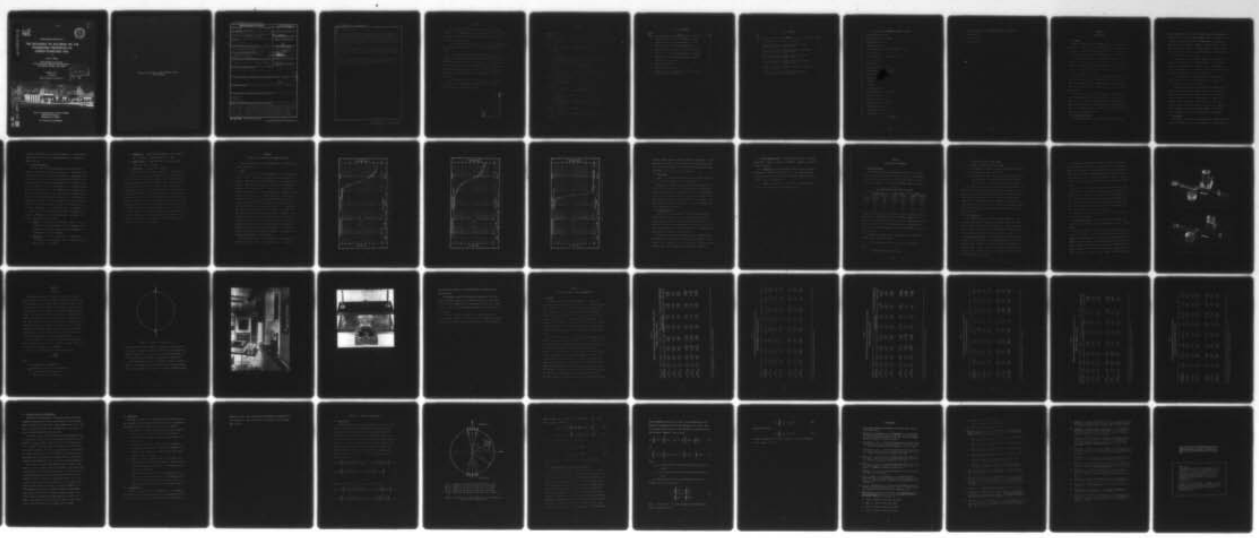

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MISCELLANEOUS PAPER S-77-14

THE INFLUENCE OF POLYMERS ON THE ENGINEERING PROPERTIES OF CEMENT-STABILIZED SOIL

by

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September 1977
Final Report

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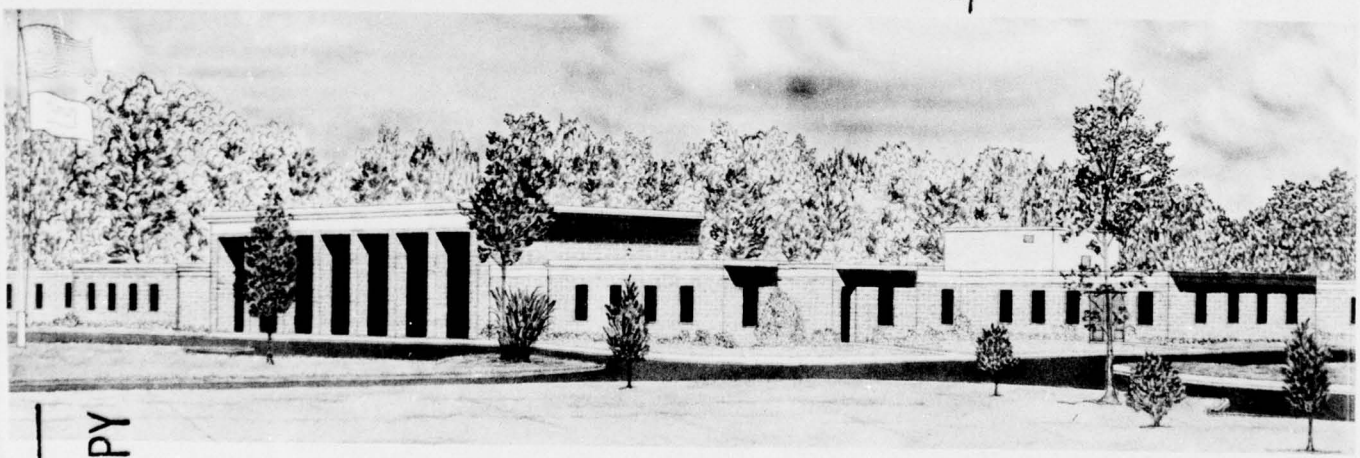

Prepared for Assistant Secretary of the Army (R&D)
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper S-77-14	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THE INFLUENCE OF POLYMERS ON THE ENGINEERING PROPERTIES OF CEMENT-STABILIZED SOIL		5. TYPE OF REPORT & PERIOD COVERED Final Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Jessie C. Oldham		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Soils and Pavements Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 4A161101A91D/02/102
11. CONTROLLING OFFICE NAME AND ADDRESS Assistant Secretary of the Army (R&D) Department of the Army Washington, D. C. 20310		12. REPORT DATE September 1977 13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) WES-MP-S-77-14		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Stabilization
Soil-Cement
Polymers
Tensile Strength

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this investigation was to determine if engineering properties of soil-cement could be significantly improved by the addition of a relatively small amount of polymeric material. Polymer science has increased drastically over the last two decades and polymers have become increasingly useful in recent years. Composite materials using polymers have been used in several areas of engineering, and it was believed that positive results could be obtained when they were used in combination with soil-cement. (Continued)

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20. Abstract (Continued).

Three soils were used in this investigation: a lean clay classified as CL by the Unified Soil Classification System (USCS), a fat clay classified as CH by the USCS, and a uniform grade sand classified as SP by the USCS. The stabilizers used included type I portland cement and two proprietary polymers. These two polymers were selected after a deliberate screening test involving numerous polymers. Indirect tensile and unconfined compressive tests were conducted on specimens containing 4, 6, and 8 percent portland cement plus 2 percent polymer.

Results are presented showing the effects of polymers on tensile strength, compressive strength, density, tensile modulus of elasticity, and compressive modulus of elasticity. Correlations are also presented between tensile and compressive strengths and tensile and compressive moduli of cement-treated soils.

Although conclusive results cannot be determined without extensive research using other polymers and other soils, it is concluded that polymers have a tremendous effect on soil-cement, and that further research should be initiated in order that the effects of various polymers on different soil types can be more accurately defined.

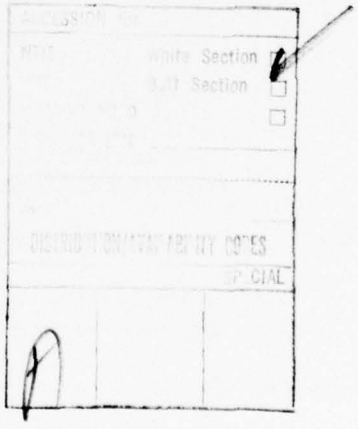
PREFACE

The investigation reported herein was conducted under the Department of the Army Project No. 4A161101A91D, In-House Laboratory Independent Research (ILIR) Program, sponsored by the Assistant Secretary of the Army (R&D).

This investigation was conducted by the U. S. Army Engineer Waterways Experiment Station (WES) in the Soils and Pavements Laboratory (S&PL).

The investigation was performed during the period April 1975 to December 1976 under the general supervision of Messrs. James P. Sale, Chief, and Richard G. Ahlvin, Assistant Chief, of the S&PL, and the direct supervision of Messrs. William L. McInnis, Chief, Materiel Development Division, and Royce C. Eaves, Chief, Stabilization Branch. Mr. Jessie C. Oldham was the principal investigator and author of this report.

COL G. H. Hilt, CE, and COL John L. Cannon, CE, were Directors of WES during the investigation and preparation of this report. Mr. F. R. Brown was Technical Director.



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LIST OF SYMBOLS, NOTATIONS, AND DEFINITIONS

C	Weight of portland cement
d	Average diameter of specimen
E	Modulus of elasticity
E_c	Compressive modulus
E_h	Tensile modulus based on horizontal deformation
E_t	Tensile modulus
E_v	Tensile modulus based on vertical deformation
G_s	Specific gravity
IDT	Indirect tensile
P	Weight of polymeric material
P_{max}	Maximum load applied to specimen
pcf	Pounds per cubic foot
psi	Pounds per square inch
PA	Polymer A
PB	Polymer B
PC	Portland cement
q_u	Unconfined compressive strength
S	Weight of air-dried soil
S_t	Maximum tensile strength
t	Average height of specimen
UC	Unconfined compression
W_i	Initial water content
W_o	Optimum water content

(Continued)

LIST OF SYMBOLS, NOTATIONS, AND DEFINITIONS (CONCLUDED)

γ_d	Dry density
ν	Poisson's ratio
ω	Water content

CHAPTER 1

INTRODUCTION

1.1 General

Man has attempted since the beginning of history to improve the properties of soil. He has used a variety of stabilization methods, but generally speaking these methods can be divided into two major types--mechanical stabilization and chemical stabilization.

Mechanical stabilization involves the reorientation of soil particles to a more stable position in order to increase strength, decrease compressibility and permeability, and control volume change. It may also involve the addition or removal of certain soil particles in order to improve the gradation.

Chemical stabilization involves the adding of chemicals such as cement, lime, asphalt, salt, polymer, etc. Through the addition of these additives the properties are changed through physicochemical reaction, mechanical bonding, plugging of soil voids, ion exchange, and absorption.

In the past, engineers have avoided marginal sites where the soil was unfavorable, but in future work the engineer will not be able to do so. He will be confronted with the challenge of using these areas. This challenge will be met through chemical stabilization. The difference in cost of property alone will more than offset the added cost of stabilization.

1.2 Objectives and Purpose

It was the objective of this research to determine if the

various parameters of soil-cement could be significantly improved by the addition of a relatively small amount of polymer. Cement is one of the most widely used materials for improving the strength and stability of soil. However, cracking is a common cause of strength loss in soil-cement. There are a number of factors that contribute to cracking of soil-cement, but the most important are probably the cohesive or tensile characteristics.

An investigation was conducted to determine if the tensile properties as well as the compressive properties of a soil-cement mixture could be significantly improved. The information gained in this investigation will be beneficial in the design of multilayered pavement systems where tensile failure may result.

With the development of high-speed digital computers and the finite element method, means have been provided to handle these tensile properties in a realistic manner.

In multilayered pavement systems where the deformation modulus differs in the various layers, tensile stresses develop under load. The maximum tensile stresses occur at the bottom of the various stabilized layers. When this stress exceeds the strength of the material, cracks form and are reflected to the surface. This phenomenon leads to the deterioration of the pavement. Improved tensile strength in stabilized base and subbase material would reduce cracking and thus reduce deterioration of the pavement.

1.3 Soil-Cement

Soil-cement is defined as a tightly compacted mixture of pulverized soil, portland cement, and water which, as the cement hydrates,

forms a hard durable structural material.[1] The Roman engineers are credited with the origination of cement by mixing lime putty and volcanic ash. Soil-cement was first used for stabilization of existing subgrades to serve as a base course for lightly trafficked roads. About 1917, Dr. J. H. Amies[1] took out a patent on a soil and cement mixture that was labeled "Soilamies." Later, in 1935, an extensive research program using soil-cement was initiated by the Portland Cement Association and the South Carolina State Highway Department. This research encouraged others to investigate soil-cement. Since then, use of soil-cement has risen to an unprecedented level. It has been used widely for over 40 years, mainly as a base course for roads and airfields and as slope protection for canals and embankments.

The changes exhibited by cement-treated soils are as follows:[2]

a. Reduced plasticity indices.

b. Increased plastic limits.

c. Reduced liquid limits (for soils with liquid limits greater than 40) or increased liquid limits (for soils with liquid limits less than 40).

d. Increased strength.

e. Reduced permeabilities.

f. Reduced volume changes.

These changes are brought about by four mechanisms or reactions: (a) hydration, (b) cation exchange, (c) carbonation, and (d) pozzolanic reaction. Of these, hydration is by far the most important.

1.4 Basic Concepts of Polymers

A polymer is a large molecule built up by the repetition of

small, simple chemical units. These units of the polymer are usually equivalent or nearly equivalent to the monomer, or starting material from which the polymer is formed. The chemical process by which monomers are converted to polymers is called polymerization. There are two major types of polymerization reactions: addition polymerization and condensation polymerization. Addition polymerization is the reaction between molecules of similar structure; these link themselves together to form the larger macromolecule without change in chemical composition. Polycondensation is the reaction between two or more dissimilar compounds which react with each other to form the macromolecule and a by-product.

Polymers are generally held together as macromolecules by covalent bonds, whereas the separate molecules or segments of the same molecule are attracted to each other by "intermolecular forces," also termed "secondary" or "van der Waals" forces. In general, the covalent bonds govern the thermal and photochemical stability of polymers while secondary forces determine most of the physical properties we associate with specific compounds.

Polymers vary from liquids and soft rubbers to very hard and rigid solids. They occur both naturally and synthetically. Natural polymers have been utilized throughout the ages. For example, asphalt was used in pre-Biblical times; amber was known to the ancient Greeks; and gum mastic was used by the Romans. About a century ago the unique properties of natural polymers were brought to light.

These polymers were later modified to make them more useful. Then the synthetic polymers were developed. Polymer science has

increased drastically over the last two decades. It is estimated that approximately 600 new polymer chemical materials are placed on the market each year.

1.5 Review of Literature

In recent years polymers have become increasingly useful due largely to their versatile mechanical properties. Composite materials using polymers have been used in several areas of engineering. Since 1965, extensive research has been done using polymers with portland cement concrete, and remarkable improvements have been made in structural and durability properties (References 3-9). Polymeric materials have also been investigated as soil stabilizers with varying results. From 1946 to 1961, extensive research was conducted by Massachusetts Institute of Technology (MIT) under contract to the U. S. Government (References 10 and 11). Some of the materials that were investigated during this period were melamines, furfurals, formaldehydes, ureas, silicates, acrylamides, vinyls, styrenes, epoxies, and acrylates.

Through this research program it was found that polymerization can have a tremendous effect on the engineering properties of soil. Some of these effects are as follows:

a. Strength. Polymerization can increase strength. It can increase tensile strength from zero to very substantial values. Compressive strength can also be improved, although not as spectacularly as tensile strength.

b. Flexibility. A soil can be made rubbery. The amount of flexibility developed depends on the soil, water content, and amount and type of treatment.

c. Permeability. Permeability is decreased by the blockage of the flow passages of water within the soil mass.

d. Compressibility. Compressibility is reduced since the polymer fills the soil voids.

e. Durability. The durability is improved.

In 1970 the Bureau of Reclamation conducted a research program to determine the feasibility of improving soil-cement properties by either incorporating a monomer into fresh soil-cement mix or impregnating hardened soil-cement with a monomer. The monomer used was methyl methacrylate. The data from this program indicate that the engineering properties of soil-cement can be improved by the addition of polymeric materials. Compressive strengths were improved by impregnation by a factor of 3.4. Premix specimens containing 3 percent methyl methacrylate also showed an increase in compressive strength, although not as great as that of impregnated specimens. Both premixed specimens and impregnated specimens showed a reduction in permeability.

The potential for improving the engineering properties of soil-cement is enormous, and it is the belief of this author that it is the next logical step in the development of soil-cement as well as in the state of the art of soil stabilization.

CHAPTER 2

DESCRIPTION OF MATERIALS AND POLYMER SELECTION

Three fine-grained soils and two polymeric materials were used in this investigation.

2.1 Soils

The soils consisted of two fine-grained clays and a fine-grained sand. The first clay, commonly referred to as Vicksburg loess, is a lean clay classified as CL by the Unified Soil Classification System (USCS). It was obtained from the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss. This soil has a liquid limit of 33 and a plasticity index of 10. Approximately 99.2 percent by weight passed the No. 200 sieve. The second clay, commonly referred to as "buckshot," is a fat clay classified as CH by the USCS. It was obtained from the low-lying areas adjacent to the Mississippi River. It has a liquid limit of 65 and a plasticity index of 41. Approximately 89.9 percent by weight passed the No. 200 sieve. The third soil, a sand, was a uniform grade and classified as SP by the USCS. It was obtained from the floodplain of the Big Black River. Approximately 87.9 percent by weight passed the No. 50 sieve and 54.3 percent by weight passed the No. 70 sieve. Grain-size analyses and specific gravities of all three soils are given in Figures 1-3. These soils were selected since they were readily available and considerable information was available on their behavior.

Sufficient quantities of each soil were obtained to assure that enough soil would be available to complete testing. All soils were

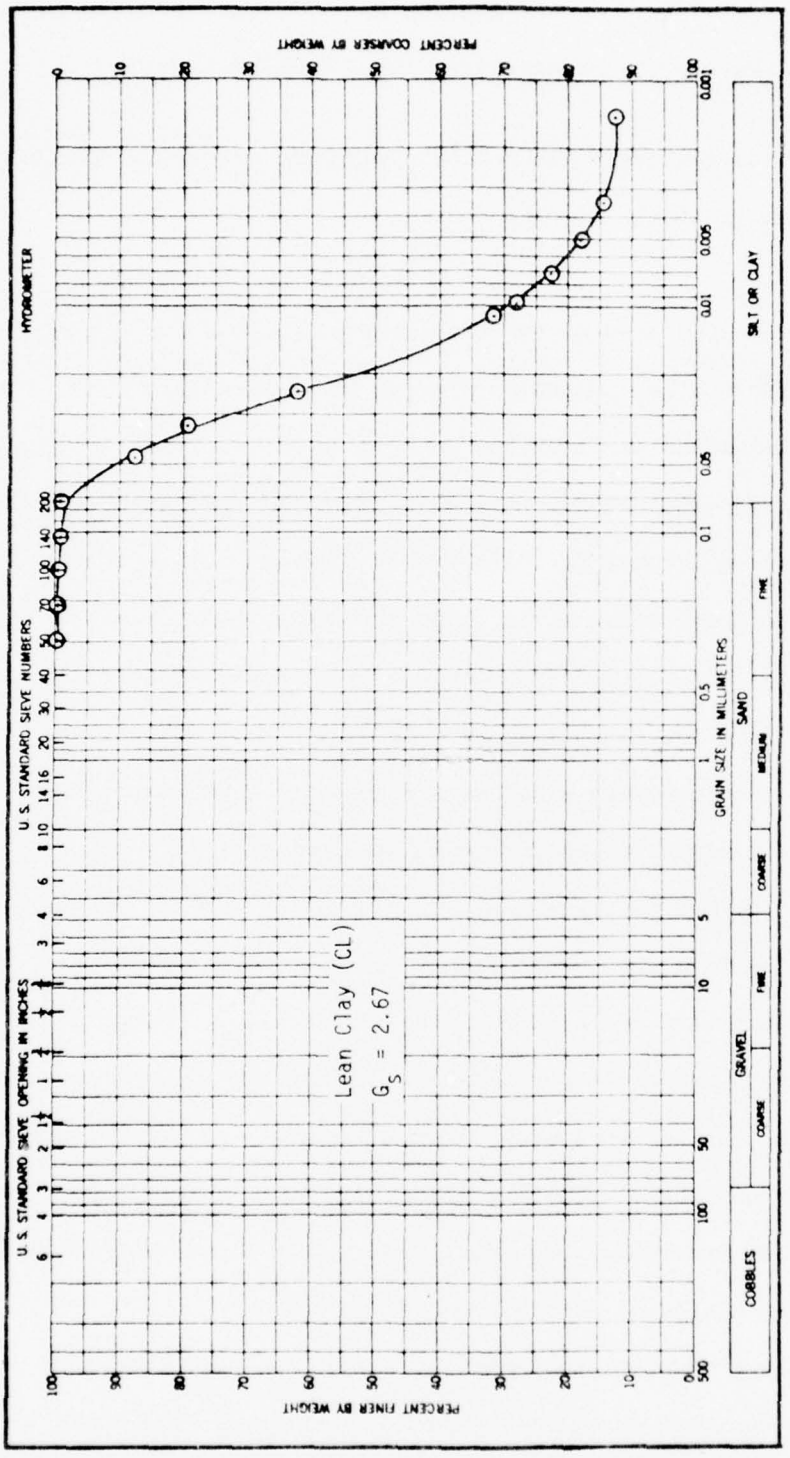


Figure 1. Gradation curve and specific gravity; lean clay

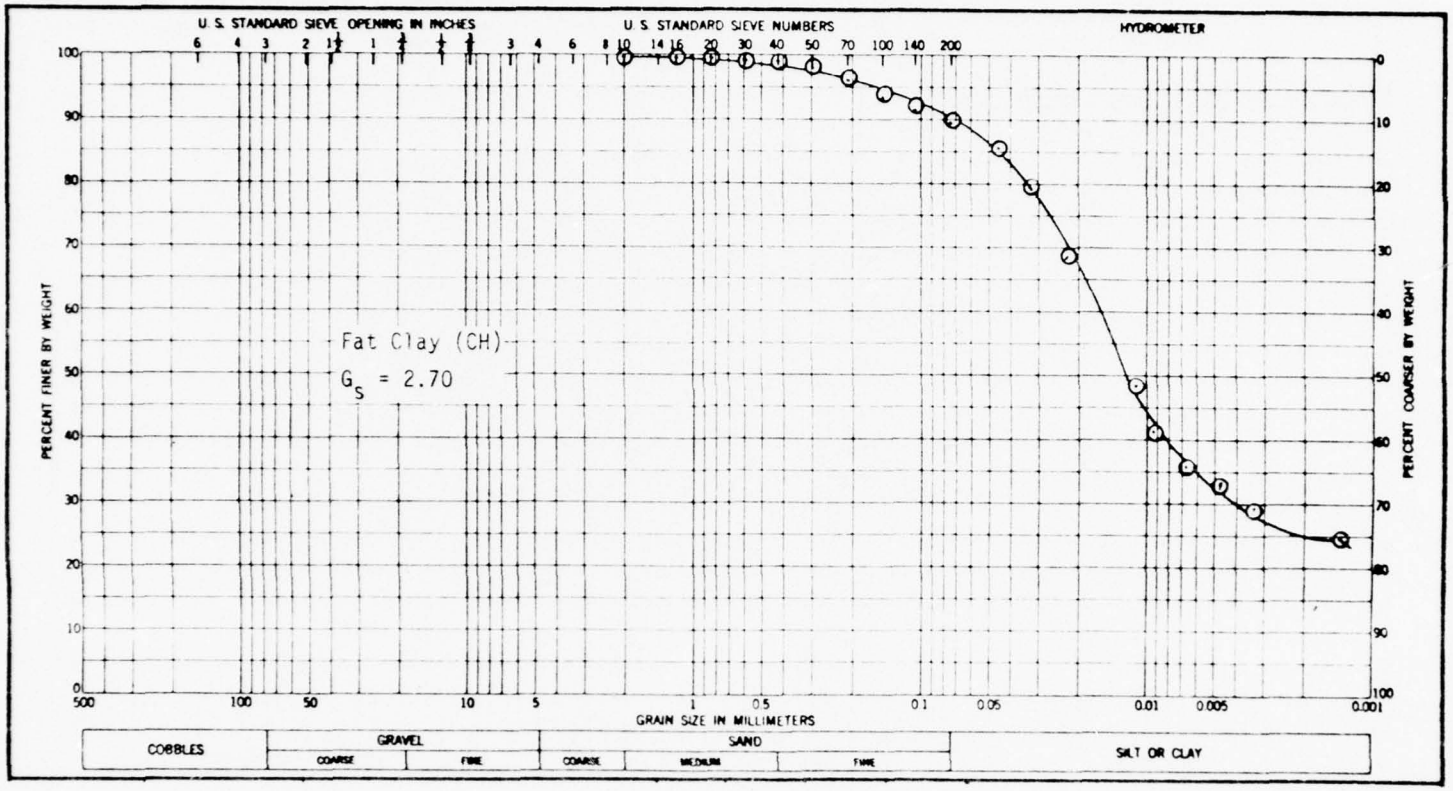


Figure 2. Gradation curve and specific gravity; fat clay

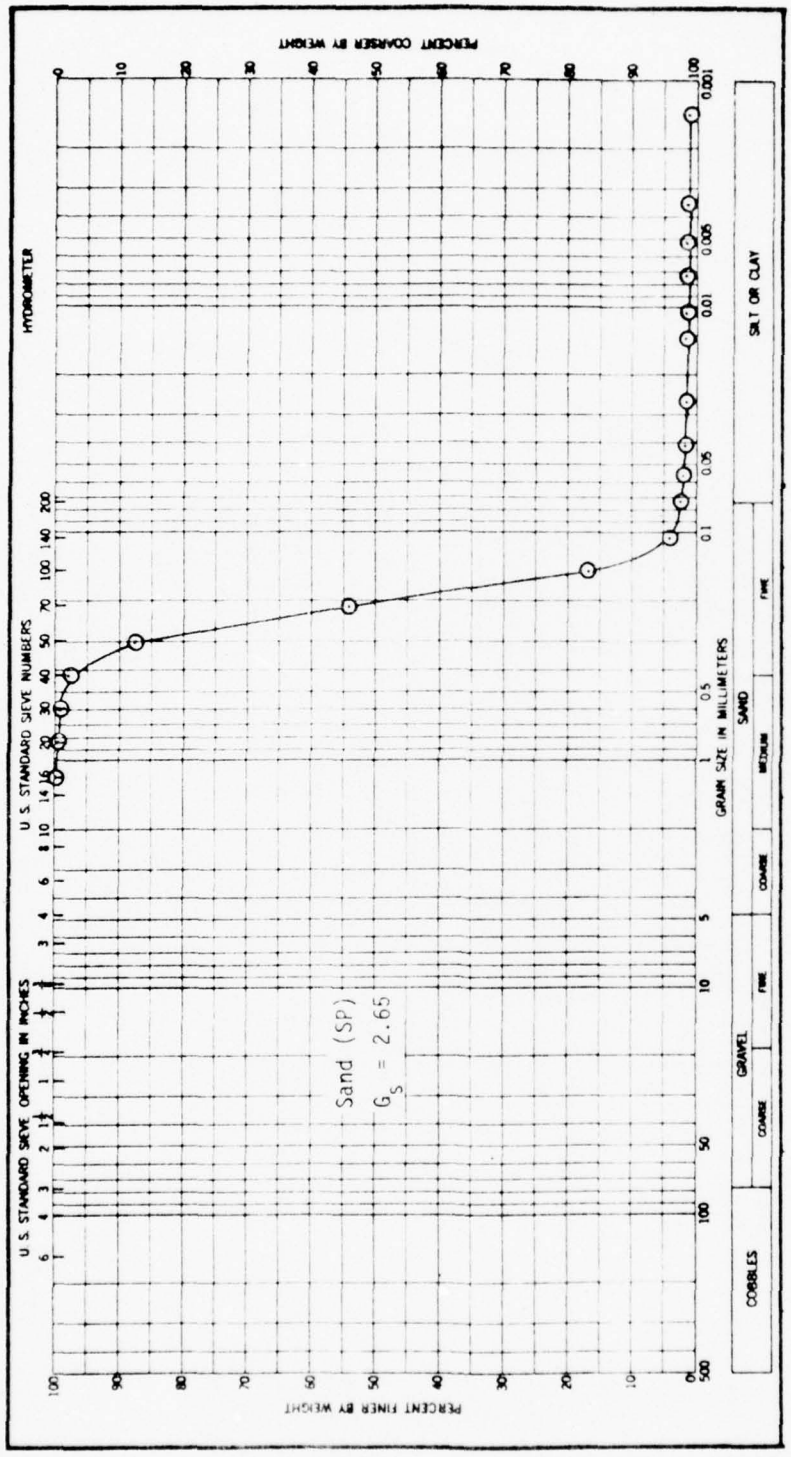


Figure 3. Gradation curve and specific gravity; sand

air-dried. Each clay was pulverized, screened through a No. 4 sieve, and mixed to uniformity. The sand was also screened through a No. 4 sieve to remove large particles. The soils were placed in airtight containers until test specimens were prepared.

2.2 Stabilizers

Cement. The primary stabilizer was portland cement designated as type I by ASTM Designation C150-74 (Reference 12).

Polymers. Two proprietary polymeric materials were tested. The first material (polymer A) was a compounded latex based on natural rubber, various synthetic rubbers, and "Kralac." It is manufactured by Uniroyal, Inc., and is designated by them as Lotol LN-7414. The second material (polymer B) was a depolymerized guar product. It is manufactured by General Mills Chemical, Inc., and is designated by them as Experimental Polymer 102.

2.3 Polymer Selection

The selection of the polymers to use was extremely difficult in that there were hundreds of materials and funds were limited. Various companies and private laboratories were contacted for polymeric material which they believed would be effective as a soil stabilizer. The materials received were tested in the laboratory using an expedient and inexpensive screening test.

Specimens of the polymeric materials for these screening tests were molded using the Harvard miniature compaction apparatus (mold size 1.31 in. in diameter by 2.82 in. in length). Only the lean clay soil was used. The following characteristics were evaluated:

a. Water compatibility. Since the material would be in a moist environment, it must be compatible with water. Ideally, it should be a water dispersant.

b. Workability. The mixing process must uniformly distribute the polymeric material throughout the soil. Prolonged mixing was also undesirable since the polymerization process might be disrupted. Compaction must be accomplished.

c. Curing. After 24 hr at 100 percent relative humidity and 74 deg F, the specimen should show signs of curing.

CHAPTER 3

PREPARATION OF SPECIMENS

3.1 Moisture Content

In order to insure that comparable specimens would be attained during testing, moisture-density tests were conducted. Optimum water contents were determined for all three soils containing 4, 6, and 8 percent cement (Table 1). The Harvard miniature compaction apparatus

Table 1

Moisture-Density Relations for Test Soils

	Lean Clay		Fat Clay		Sand	
Portland Cement %	Optimum Moisture Content %	Maximum Dry Density pcf	Optimum Moisture Content %	Maximum Dry Density pcf	Optimum Moisture Content %	Maximum Dry Density pcf
4	18.8	107.4	22.8	102.2	14.2	102.1
6	18.5	107.3	22.0	102.7	12.2	103.4
8	18.9	107.9	21.5	102.6	12.9	104.4

was utilized in determining these water contents. Compaction was applied on each of five layers using an effort of 10 tamps per layer with a 40-lb spring. This effort is comparable to the Standard Proctor test. (A more detailed explanation of sample preparation is discussed in Section 3.2.)

The amount of additional water required to obtain optimum water content was calculated as follows:

$$(S + C + P)(W_o + 0.01) - (S \times W_i) = \text{ml of } H_2O \text{ required}$$

where

S = weight of air-dried soil, grams

C = weight of portland cement, grams

P = weight of polymeric material, grams

W_o = optimum water content or desired molding water content, %

W_i = initial water content of soil, %

0.01 = an evaporation factor derived from prior experience in the WES Laboratory. This factor has proven to be effective when mixing these soils under the conditions outlined

The amount of water calculated was then mixed with S grams of air-dried soil. Mixing was accomplished with a Bledsoe mixer. The soil was then screened through a No. 4 sieve, placed in airtight containers, and allowed to equilibrate for 24 hr before molding of specimens. Quantities of 2000 grams of soil were prepared in this manner. This small quantity was selected in order to insure accuracy and uniformity. The amount was adequate to prepare one tensile specimen and one compressive specimen.

3.2 Soil Preparation

Six 2000-gram quantities of each soil were prepared at a time. This was enough soil to complete an entire test series. Six tensile and six compressive specimens were molded. This number of specimens could be molded in one day, and this was desirable in order to maintain uniformity in specimen preparation as well as curing.

Mixing of stabilizers. The process of mixing two or more stabilizers in a soil is important in attaining homogeneity. It is often difficult since the additives involved are only a small portion of the total mass. Because of this, it was necessary that mixing procedures for each polymeric material be considered in order to attain the highest degree of homogeneity.

The first step in mixing was to add the correct percentage of portland cement and thoroughly hand mix for 2 min. If the specimen was a control specimen (no polymeric additive), hand mixing was continued for an additional 2 min, and then the specimen was molded. If the specimen was a test specimen (with polymeric additive), the polymer was added and mixing was continued for an additional 2 min before molding.

The difference in the procedures was the method used to add the polymeric additive. Polymer A, a latex, was added by diluting the latex with part of the water calculated to obtain optimum water content. This procedure of introducing the latex was necessary since the concentrated latex could not be distributed uniformly over the mass. The concentrated latex would agglomerate during mixing with only a small amount of the soil-cement mixture.

Polymer B was in powdered form and thus could be added directly to the soil-cement mixture.

Molding of specimens. Tensile and compressive specimens were molded using 4, 6, and 8 percent portland cement plus 0 and 2 percent polymer.

Tensile specimens for the clay soils were molded in a standard 4- by 4.5-in. stainless steel mold using a 2.5-in. steel filler. This apparatus is shown in Figure 4. These clay specimens were extruded immediately after molding. Sand specimens could not be molded utilizing the standard mold because they could not be extruded without damaging the specimen. These specimens were molded using the apparatus shown in Figure 5. It consists of (a) a paper cylinder mold having

Figure 4. Apparatus used for molding clay tensile specimens

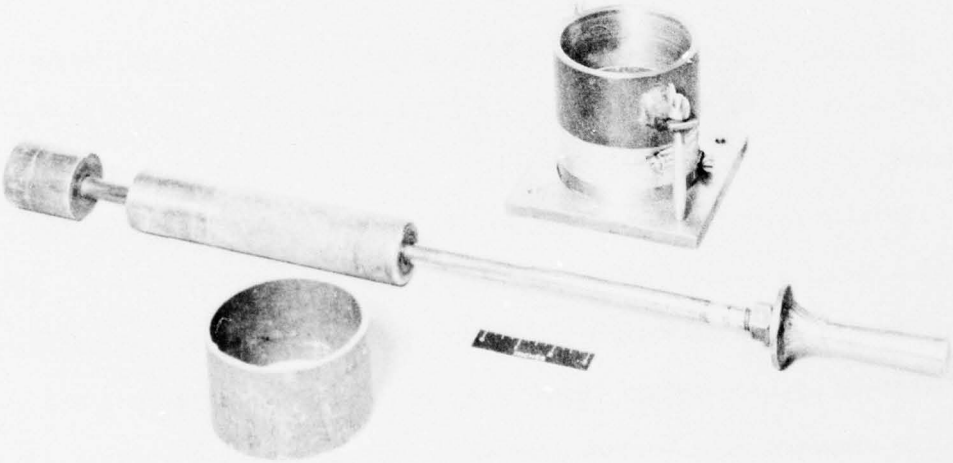


Figure 5. Apparatus used for molding sand tensile specimens

walls approximately 0.13 in. thick, an inside diameter of 4 in., and a height of 2.5 in., and (b) a metal jacket and two metal bands to provide reinforcing during molding. After molding, the reinforcing was removed but the specimen was allowed to remain in the paper cylinder during curing. Immediately before testing, these cylinders were torn off.

Compaction of all tensile specimens was attained in three layers using a 5.5-lb hammer falling 12 in. with 13 blows per layer. Densities attained were comparable to those attained using the Standard Proctor test.

The Harvard compaction apparatus (2.82 in. long and 1.31 in. in diameter) was used to prepare the compressive specimens. This device applies kneading compaction and by using a 40-lb compaction spring, 5 layers, and 10 tamps per layer, it was possible to closely approximate the densities obtained from the Standard Proctor test. This effort was used by Freitag,[13] which was a modification of work done by Wilson.[14] Further study at Oklahoma State University by Nagih M. El-Rawi and others[15] indicated that comparable densities can be obtained.

Curing. All specimens were cured for 7 days in a room maintained at 68 to 72 deg F and 95 to 100 percent relative humidity. A 7-day cure period was chosen because it seemed to be a reasonable length of time to insure sufficient strength gains so as to make possible comparable results.

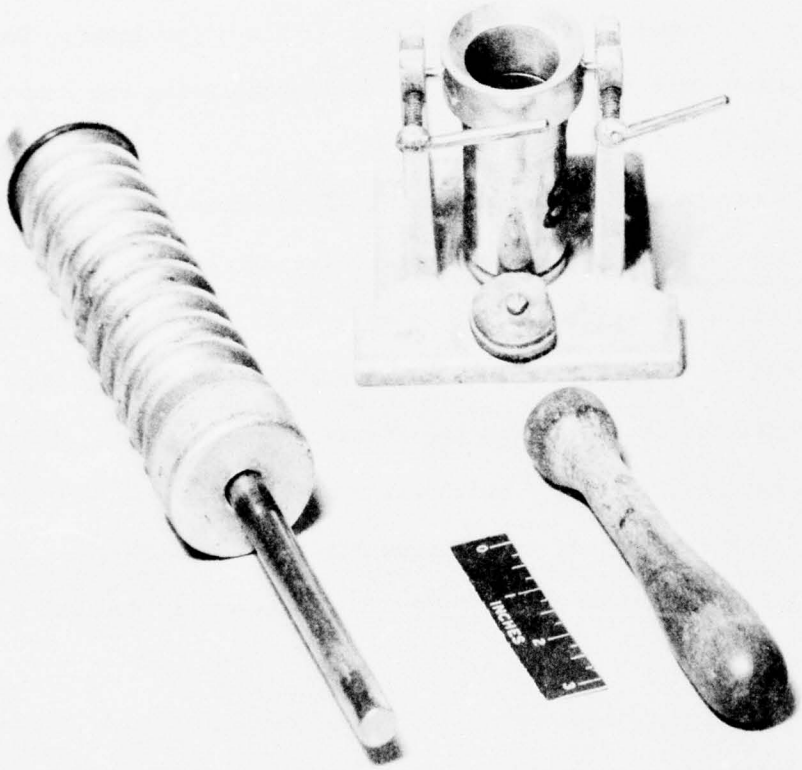


Figure 6. Apparatus used for molding compressive specimens

CHAPTER 4

TESTING

Testing was divided into two series, series A and series B, which included both tensile and compressive testing of specimens involving polymers A and B, respectively. The indirect tensile (IDT) test was utilized for determining tensile properties and the unconfined compression (UC) test was used to determine compressive properties. The indirect tensile test was chosen over other tensile tests because of its well-defined theory, ease of molding, and ease of testing. This test, which was developed independently by Carneiro and Barcellos[16] in Brazil and Akazawa[17] in Japan in 1953, is a simple application of diametral compressive loads along two opposite generatrices (Figure 7). This condition results in failure in tension along the dimetral plane formed by the two generatrices.

If the specimen is considered to be homogeneous and isotropic and to obey Hooke's law, the tensile strength, Poisson's ratio, and the modulus of elasticity can be evaluated.

The tensile strength at failure can be expressed as

$$S_t = \frac{2P_{max}}{\pi t d}$$

where

S_t = maximum tensile strength, psi

P_{max} = maximum load applied to the specimen, lb

t = average height of specimen, in.

d = average diameter of specimen, in.

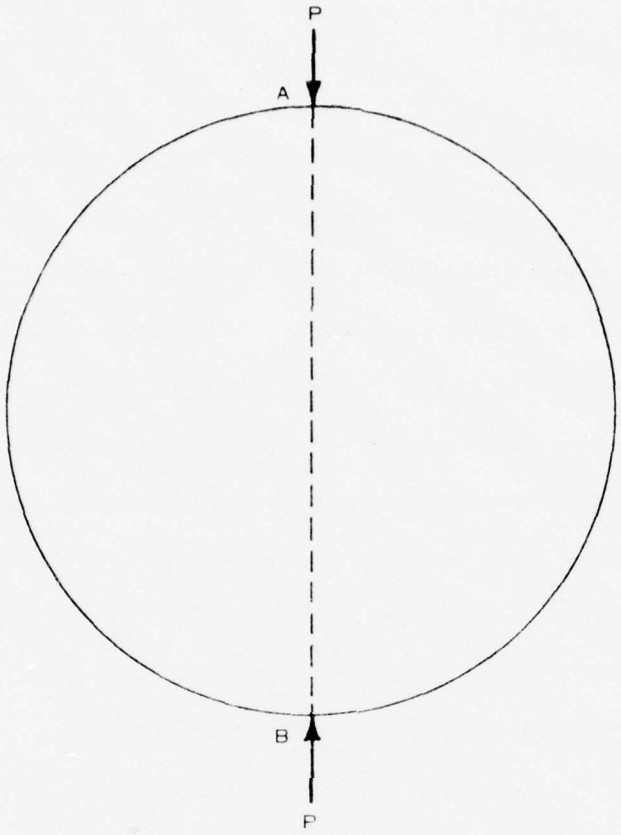


Figure 7. Schematic of tensile test

Poisson's ratio (ν) and the modulus of elasticity (E) can be evaluated using an approach of Hadley et al.[18] based upon an analysis by Hondros[19] in which ν, E_v, and E_h are calculated from the vertical and horizontal deformation, respectively (see Appendix A).

The equipment used to test the specimens in tension is shown in Figure 8. It consists of an Instron Model 1116, 50,000-lb universal tester and an indirect tensile device. The Instron provided loading

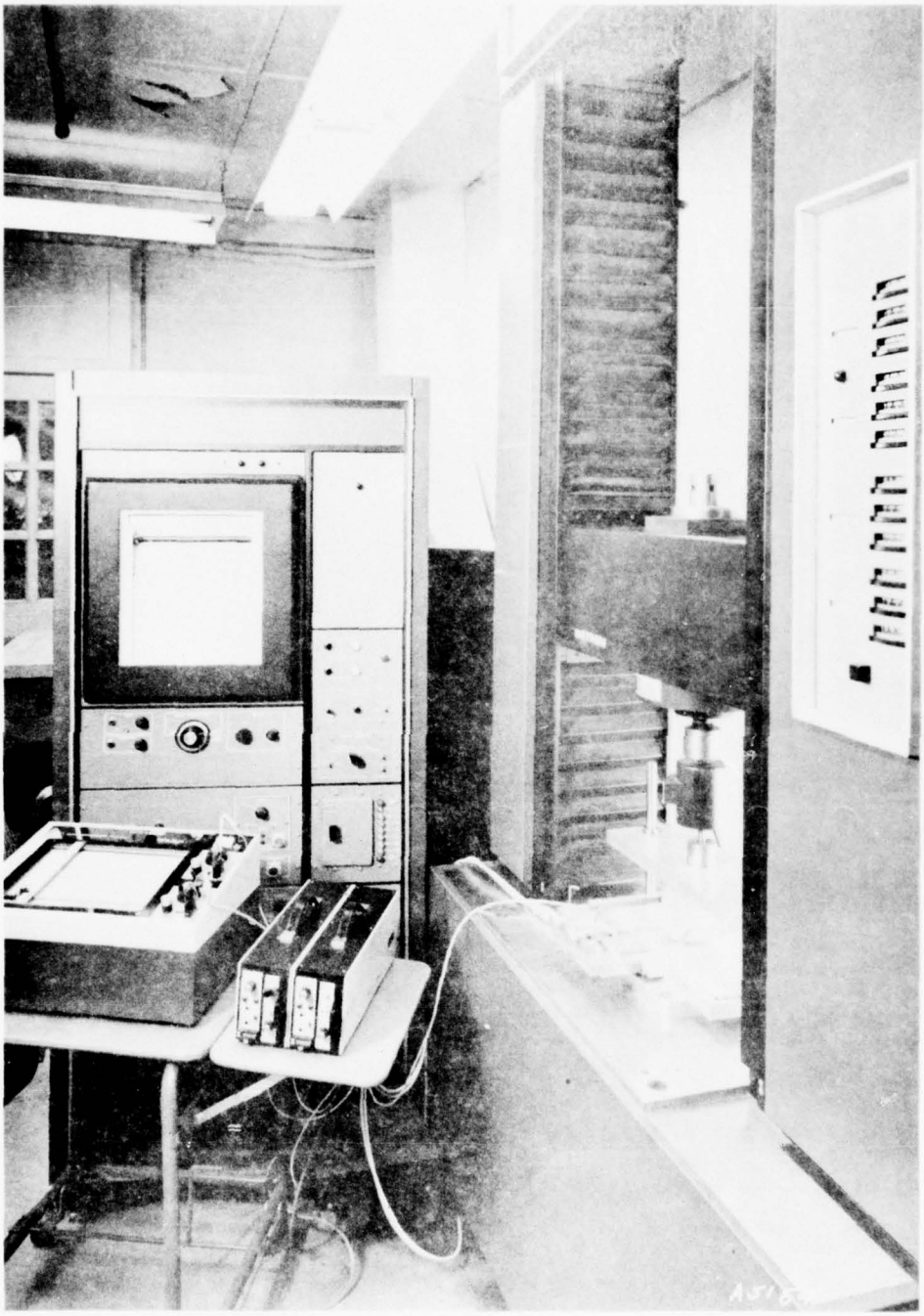


Figure 8. Tension test apparatus

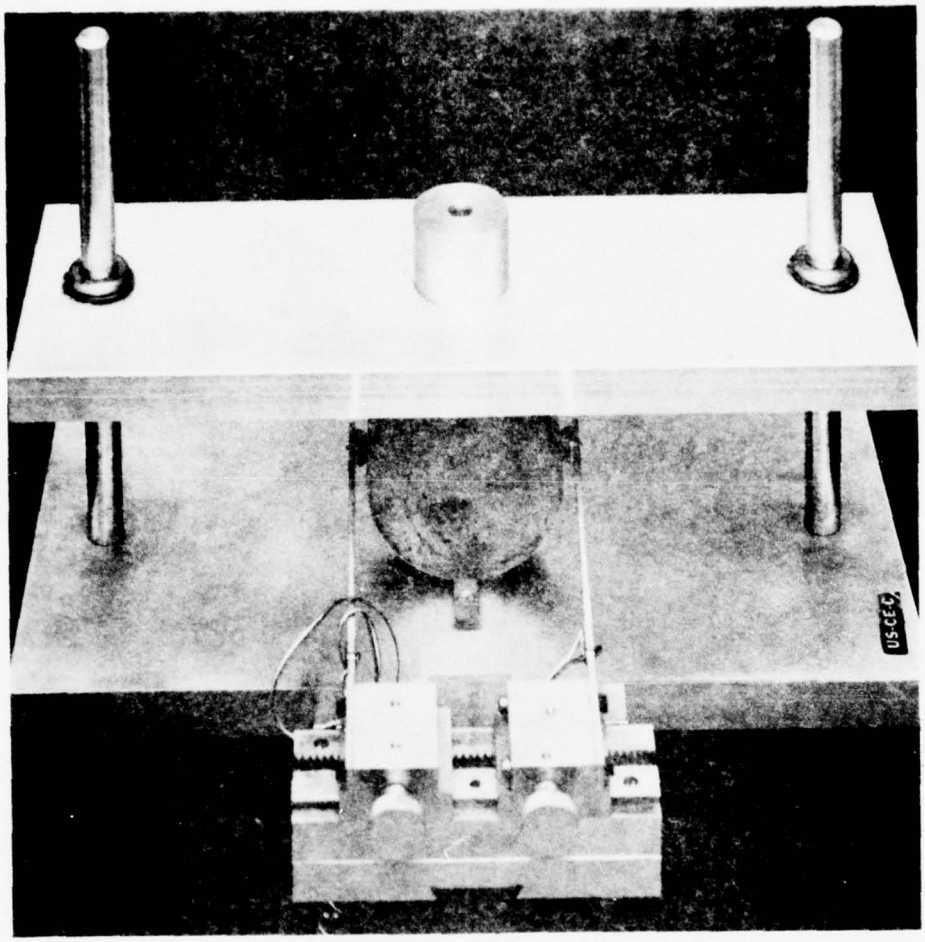


Figure 9. Indirect tensile device

at the rate of 0.002 in./min and plotted the load versus vertical deflection. The indirect tensile device shown separately in Figure 9 consists of lower and upper platens. The lower platen is 18 in. long by 9 in. wide. The upper platen is 18 in. long by 6 in. wide. Both platens are made of 1-in.-thick aluminum. Two stainless steel guide posts, 3/4 in. in diameter and 12 in. high, are used to align the vertical movement. These guide posts are fixed to the lower platen,

and bushings are provided in the upper platen to reduce friction during loading.

An adjustable cantilever arm system is connected to the lower platen to measure changes in the transverse direction. These cantilever arms are instrumented with strain gages that read to the nearest 0.001 in. The load versus transverse deflection is plotted using an x-y plotter.

Unconfined compression specimens were loaded at the rate of 0.02 in./min until failure. From these data, the compressive strength at failure (q_u) and the initial tangent modulus (E_c) were determined.

CHAPTER 5

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

5.1 General

Results of this investigation are summarized in Tables 2-7. These data reveal that polymers can have both a positive and a negative effect on the soils tested. With the exception of the unrealistic values obtained for Poisson's ratio, these data appear accurate. It is believed that these unrealistic values obtained for Poisson's ratio were due to the inability to accurately measure deformation. The deformation in the transverse direction was extremely small and difficult to measure, and the vertical deformation recorded is believed to be larger than actual deformation due to the penetration of the loading strips.

Since Poisson's ratios for cement-treated fine-grained soils have generally exhibited values ranging from 0.15 to 0.35, a value of 0.35 was assumed, and tension modulus values were recalculated. These modulus values are designated as modified E_v and modified E_h in Tables 2-7. A selection of 0.35 can be further justified by pointing out that the tensile stress and tensile strain are relatively insensitive to Poisson's ratio. Hadley et al.[20] reported in 1972 that a variation in Poisson's ratio from 0.125 to 0.375 resulted in a maximum difference in tensile stresses and tensile strains of 15 percent and 8 percent, respectively. Although this investigation was limited and further study is indicated, it is believed that the results presented do show the tremendous effects, both negative and positive,

Table 2

Modulus of Elasticity Values for Lean Clay Using Portland Cement and Polymers A and B

Percent Stabilizer*	IDT ω, %	IDT γ_d, pcf	E_h psi × 10^5	E_v psi × 10^5	Poisson's Ratio Experimental	Poisson's Ratio Assumed	Modified E_h psi × 10^5	Modified E_v psi × 10^5
4PC	11.8	106.0	0.285	0.225	-0.20	0.35	2.500	0.223
4PC + 2PA	10.9	100.2	0.188	0.236	-0.22	0.35	2.281	0.234
6PC	12.0	106.2	0.381	0.324	-0.21	0.35	4.176	0.321
6PC + 2PA	11.6	101.1	0.549	0.316	-0.24	0.35	11.260	0.313
8PC	11.5	106.0	0.951	0.520	-0.20	0.35	8.496	0.515
8PC + 2PA	12.0	100.7	0.974	0.364	-0.21	0.35	9.873	0.361
4PC	16.7	106.3	0.00314	0.0272	-0.25	0.35	1.00	0.0269
4PC + 2PB	16.2	99.3	0.0238	0.0127	-0.21	0.35	0.246	0.0126
6PC	16.8	107.6	0.0199	0.0159	-0.26	0.35	1.78	0.0158
6PC + 2PB	16.4	99.8	0.0296	0.0151	-0.23	0.35	0.420	0.0149
8PC	16.0	106.5	0.0377	0.0381	-0.26	0.35	2.00	0.0377
8PC + 2PB	16.4	99.7	0.0415	0.0167	-0.22	0.35	0.525	0.0166

* PC = portland cement; PA = polymer A; PB = polymer B.

Table 3

Tensile and Compressive Results Using Lean Clay with Portland Cement and Polymers A and B

Percent Stabilizer*	UC ω, %	UC γ_d, pcf	q_u psi	E_c psi × 10^5	S_t psi	$E_t = E_v$ psi × 10^5	S_t/q_u	E_t/E_c
4PC	12.9	104.9	216.8	0.226	32.8	0.223	0.15	0.99
4PC + 2PA	11.8	101.1	231.6	0.188	29.6	0.234	0.13	1.24
6PC	13.1	106.2	312.8	0.318	42.3	0.321	0.14	1.01
6PC + 2PA	12.1	99.6	301.5	0.286	44.1	0.313	0.15	1.09
8PC	12.6	105.8	385.8	0.581	52.0	0.515	0.13	0.89
8PC + 2PA	12.2	101.0	377.5	0.427	50.7	0.361	0.13	0.85
4PC	14.8	105.8	198.9	0.250	24.7	0.0269	0.12	0.11
4PC + 2PB	14.8	101.7	178.0	0.106	15.6	0.0126	0.09	0.12
6PC	15.0	105.8	246.6	0.298	36.4	0.0158	0.15	0.05
6PC + 2PB	14.9	102.3	260.3	0.157	23.4	0.0149	0.09	0.09
8PC	14.3	105.4	360.2	0.395	42.6	0.0377	0.12	0.10
8PC + 2PB	14.1	102.1	259.5	0.184	20.8	0.166	0.08	0.09

* PC = portland cement; PA = polymer A; PB = polymer B.

Table 4

Modulus of Elasticity Values for Fat Clay Using Portland Cement and Polymers A and B

Percent Stabilizer*	IDT ω, %	IDT γ_d, pcf	E_h psi × 10^5	E_v psi × 10^5	Poisson's Ratio Experimental	Poisson's Ratio Assumed	Modified E_h psi × 10^5	Modified E_v psi × 10^5
4PC	17.2	93.2	0.0576	0.0438	0.12	0.35	0.0914	0.0437
4PC + 2PA	16.5	96.7	4.84	1.18	2.27	0.35	1.18	0.122
6PC	16.8	95.3	0.106	0.0650	-0.10	0.35	0.386	0.0644
6PC + 2PA	16.9	96.9	0.454	0.114	-0.10	0.35	1.60	0.113
8PC	17.3	95.7	0.184	0.0674	-0.14	0.35	0.905	0.0668
8PC + 2PA	17.0	98.0	0.675	0.212	-0.03	0.35	1.73	0.210
4PC	21.6	95.2	0.0125	0.0102	-0.26	0.35	0.695	0.0101
4PC + 2PB	21.9	90.4	0.0159	0.0596	-0.23	0.35	0.257	0.00590
6PC	21.5	92.0	0.0178	0.00869	-0.26	0.35	1.42	0.00860
6PC + 2PB	22.7	89.3	0.0208	0.00629	-0.18	0.35	0.144	0.00623
8PC	21.6	95.8	0.00910	0.0101	-0.26	0.35	1.03	0.0100
8PC + 2PB	22.1	91.4	0.0293	0.00994	-0.24	0.35	0.524	0.00984

* PC = portland cement; PA = polymer A; PB = polymer B.

Table 5

Tensile and Compressive Results Using Fat Clay with Portland Cement and Polymers A and B

Percent Stabilizer*	UC ω, %	UC γ_d, pcf	q_u psi	E_c psi × 10^5	S_t psi	$E_t = E_v$ psi × 10^5	S_t/q_u	E_t/E_c
4PC	17.6	92.7	107.8	0.0599	7.79	0.0437	0.07	0.73
4PC + 2PA	18.3	94.8	103.0	0.0676	22.2	1.22	0.22	1.80
6PC	17.0	95.6	143.7	0.0774	11.1	0.0644	0.08	0.87
6PC + 2PA	17.8	95.7	173.6	0.106	25.8	0.113	0.15	1.07
8PC	17.3	93.9	132.8	0.0772	12.4	0.0668	0.09	0.87
8PC + 2PA	17.8	95.5	190.5	0.136	33.5	0.210	0.18	1.54
4PC	21.7	94.2	65.3	0.108	13.2	0.0101	0.20	0.09
4PC + 2PB	20.3	92.9	152.7	0.116	10.0	0.00590	0.07	0.05
6PC	21.2	96.4	124.8	0.176	12.5	0.00860	0.10	0.05
6PC + 2PB	20.0	92.7	166.8	0.116	8.12	0.00623	0.05	0.05
8PC	20.9	97.8	190.1	0.201	17.3	0.0100	0.09	0.05
8PC + 2PB	21.7	94.4	130.3	0.139	11.8	0.00984	0.09	0.07

* PC = portland cement; PA = polymer A; PB = polymer B.

Table 6

Modulus of Elasticity Values for Sand Using Portland Cement and Polymers A and B

Percent Stabilizer*	IDT ω, %	IDT γ_d, pcf	E_h psi × 10^3	E_v psi × 10^3	Poisson's Ratio Experimental	Poisson's Ratio Assumed	Modified E_h psi × 10^3	Modified E_v psi × 10^3
4PC	11.5	100.1	0.562	0.563	-0.26	0.35	31.54	0.562
4PC + 2PA	10.1	98.6	0.425	0.442	-0.15	0.35	2.138	0.439
6PC	11.4	100.9	0.765	0.762	-0.26	0.35	45.7	0.754
6PC + 2PA	10.4	100.7	0.564	0.555	-0.27	0.35	527	0.549
8PC	9.7	101.4	1.02	1.01	-0.27	0.35	243.4	0.995
8PC + 2PA	8.4	102.4	0.196	0.194	-0.27	0.35	793.7	0.192
4PC	7.8	102.0	0.188	0.211	-0.23	0.35	2.86	0.209
4PC + 2PB	12.8	92.9	0.471	0.238	-0.18	0.35	3.308	0.238
6PC	9.0	101.6	0.583	0.515	-0.25	0.35	49.8	0.509
6PC + 2PB	11.6	98.4	0.656	0.299	-0.18	0.35	4.363	0.296
8PC	7.7	104.9	1.35	1.38	-0.27	0.35	2729	1.36
8PC + 2PB	10.8	99.1	1.31	0.778	-0.05	0.35	3.75	0.772

Note: The series using polymer B was cured 14 days rather than 7 days.

* PC = portland cement; PA = polymer A; PB = polymer B.

Table 7

Tensile and Compressive Results Using Sand with Portland Cement and Polymers A and B

Percent Stabilizer*	UC ω, %	UC γ_d, pcf	q_u psi	E_c psi × 10^3	S_t psi	$E_t = E_v$ psi × 10^3	S_t/q_u	E_t/E_c
4PC	1.1	97.1	24.6	5.29	2.79	0.562	0.11	0.11
4PC + 2PA	1.9	98.2	44.6	40.7	2.34	0.439	0.05	0.01
6PC	1.0	96.1	39.6	3.00	4.35	0.754	0.11	0.25
6PC + 2PA	1.5	97.8	84.8	20.6	5.90	0.549	0.07	0.03
8PC	2.2	99.8	96.9	20.5	5.69	0.995	0.06	0.05
8PC + 2PA	1.9	99.1	175.2	53.0	9.25	0.192	0.05	0.01
4PC	1.1	99.2	31.3	6.22	1.98	0.209	0.06	0.03
4PC + 2PB	3.7	99.8	121.9	34.9	5.83	0.238	0.05	0.01
6PC	1.4	98.6	38.5	9.91	3.19	0.509	0.08	0.05
6PC + 2PB	3.9	102.5	244.5	29.8	9.03	0.296	0.04	0.01
8PC	1.9	100.2	75.7	20.8	8.65	1.36	0.11	0.07
8PC + 2PB	3.7	102.0	341.16	49.4	11.2	0.772	0.03	0.01

Note: The series using polymer B was cured 14 days rather than 7 days.

* PC = portland cement; PA = polymer A; PB = polymer B.

that polymeric materials can have on the engineering properties of soils.

5.2 Modulus of Elasticity

Three moduli values were examined in this investigation: E_h, the tensile modulus based on the horizontal deformation; E_v, the tensile modulus based on the vertical deformation; and E_c, the compressive modulus, taken as the initial tangent modulus.

In the lean clay mixture, the addition of polymer B in conjunction with the portland cement resulted in a reduction of all three moduli; addition of polymer A resulted in a reduction of the moduli in six of the nine instances. For fat clay mixture, polymer B resulted in a decrease in the moduli in eight of the nine instances; however, polymer A produced a significant increase in all three moduli. For sand mixture, both polymers produced a general decrease in the tensile moduli but an increase in the compressive modulus.

5.3 Density

In general, it is considered in cement stabilization that a decrease in density is related to the material properties, and that higher densities result in corresponding higher strengths. This was not the case in 10 out of 36 instances in which a polymer was added to the cement mixtures. The use of polymer B resulted in a decrease in density in all three soil-cement mixtures. Polymer A produced no effect in fat clay mixtures and little effect in sand mixtures, but caused an average decrease of 4.9 percent in density in the lean clay mixtures. The reason for this is not known. It could be due to a

oaming action which is a common occurrence with polymers, or it could e an effect similar to that which is customary when lime is added to lime-reactive soil, this behavior being attributed to the agglomerting of the fine grains creating a more granular soil and hence a igher void ratio for the same compaction effort. However, any theory t this time would be strictly speculation without further testing.

.4 Strength

Tensile strength and compressive strength were improved by the ddition of polymer A to the fat clay and sand mixtures, but no ignificant strength gain was recorded when polymer A was added to he lean clay mixtures. Tensile strength gains averaged 162 percent n the fat clay mixtures and 28 percent in the sand mixtures. Compressive strength was increased an average of 21 percent in the fat lay mixtures and 92 percent in sand mixtures.

Polymer B increased the tensile and compressive strengths of he sand mixtures and the compressive strength of the fat clay mixures. The compressive strength of the sand mixtures was increased n average of 391 percent and the tensile strength was increased an verage of 135 percent. The fat clay mixtures containing polymer B ndicated an increase of 133 percent and 34 percent in compressive trength for 4 and 6 percent cement, respectively. A reduction in ompressive strength was recorded for the specimen containing 8 perent cement. The tensile strength of the fat clay mixtures showed a ecrease as did the tensile and compressive strengths of the lean lay mixtures.

5.5 Tensile-Compressive Correlations

These data were examined for correlations between tensile and compressive parameters and compared with results of other investigations to indicate that interactions between parameters do exist. However, it is pointed out that these correlations will vary due to soil type, specimen preparation, and strain rate.

The average S_t/q_u values obtained for cement-treated soils were 0.13 for the lean clay, 0.11 for the fat clay, and 0.08 for the sand. Thompson[21] reported S_t/q_u values of 0.10 to 0.15 for lime-treated soils. Malhotra[22] recorded S_t/q_u values of 0.09 to 0.16 for various concrete mixtures. Average S_t/q_u values of 0.17 were reported for cement-stabilized silty clay by Townsend.[23] Based on the values obtained by these investigators, it appears that the S_t/q_u values obtained in this investigation are in line with other investigations.

The E_t/E_c ratios for cement-treated clays in series A ranged from 0.73 to 1.01. However, Bofinger[24] reported E_t/E_c values ranging from 0.09 to 0.13 for cement brick earth. The E_t/E_c values obtained for cement-treated clays in series B are more in line with Bofinger's findings. These ratios varied from 0.05 to 0.11. This variance in series A and B was attributed to a 3 to 4 percent variance in as-treated moisture content. Yet, this conclusion is not valid when moisture contents obtained by Bofinger are considered, since he also had a 2 percent variance in moisture content. The E_t/E_c ratios for cement-treated sand ranged from 0.01 to 0.25. In order to determine if exact correlations do exist for these parameters, a more detailed research program will be necessary.

5.6 Conclusions

Although conclusive results cannot be determined without extensive research using other polymers and other soils, the following conclusions are drawn based on the results of this investigation:

a. The addition of polymer A caused both tensile and compressive strength gains in the fat clay (CH) and the sand (SP).

b. Both polymer A and polymer B caused negative results in the lean clay (CL).

c. The addition of polymer B caused tensile and compressive strength gains in sand (SP). Compressive strength was also improved using polymer B in the fat clay (CH), but tensile strength showed a reduction.

d. Specimens containing polymers tend to form a film on the outer surface which decreases the amount of moisture lost to evaporation, resulting in slow cure. This phenomenon is believed to aid hydration.

e. The indirect tensile test is very simple and easy to use; however, it does have shortcomings in determining Poisson's ratio and Young's modulus. It is considered to be an adequate means of determining the tensile strength of the soil.

5.7 Recommendations

Based on the results of this investigation, it is recommended that further work be initiated in order to more completely define the effects of various polymers on different soil types with particular

emphasis on sands. The possibilities have hardly been explored, and the few results to date already show the tremendous effect polymers have on soils.

APPENDIX A: THEORY OF CIRCULAR DISK

A.1 Introduction

The mathematical analysis for a circular disk of radius R subjected to a concentrated load acting along the diameter was first developed by Hertz in 1883 and was later refined by Frocht,[25] Timoshenko and Goodier,[26] and others. A method for calculating the stresses and deformations in a circular disk acted upon by a uniform radial load on a small section of the disk as shown in Figure A1 was first reported by Peltier[27] in 1954 and Hondros[19] in 1959. Using Hondros' notation (see Figure A1), the stresses along the x and y axes may be expressed as follows. For stresses along the vertical diameter (y axis),

$$\sigma_{\theta y} = \frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{1 - 2r^2/R^2 \cos 2\alpha + r^4/R^4} - \tan^{-1}\frac{(1 + r^2/R^2)}{(1 - r^2/R^2)}\tan\alpha\right] \quad (A1)$$

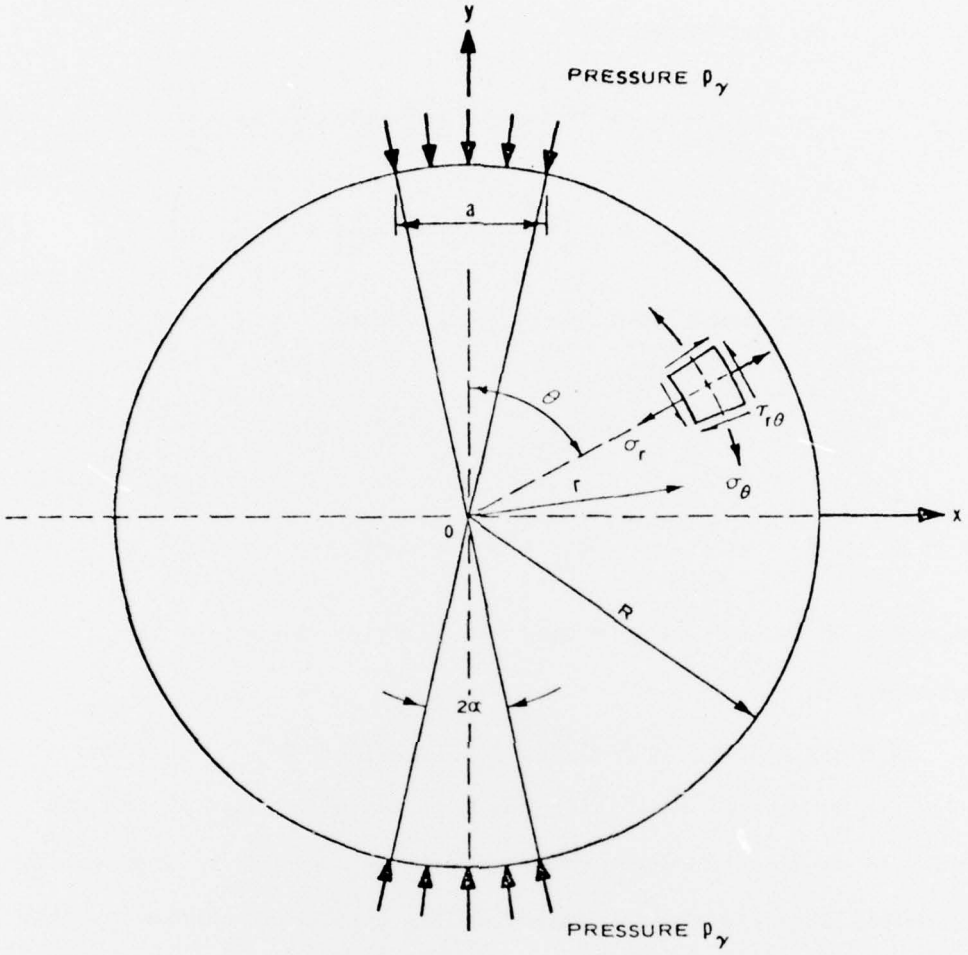
$$\sigma_{ry} = \frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{(1 - 2r^2/R^2)\cos 2\alpha} + \tan^{-1}\frac{(1 + r^2/R^2)}{(1 - r^2/R^2)}\tan\alpha\right] \quad (A2)$$

$$\tau_{r\theta} = 0 \quad (A3)$$

and for stresses along the horizontal diameter (x axis),

$$\sigma_{\theta x} = -\frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{1 + 2r^2/R^2 \cos 2\alpha + r^4/R^4} + \tan^{-1}\frac{(1 - r^2/R^2)}{(1 + r^2/R^2)}\tan\alpha\right] \quad (A4)$$

$$\sigma_{rx} = \frac{2p}{\pi}\left[\frac{(1 - r^2/R^2)\sin 2\alpha}{1 + 2r^2/R^2 \cos 2\alpha + r^4/R^4} - \tan^{-1}\frac{(1 - r^2/R^2)}{(1 + r^2/R^2)}\tan\alpha\right] \quad (A5)$$



$\sigma_{\theta x}$, σ_{rx} TANGENTIAL AND RADIAL STRESSES ALONG THE Ox AXIS
$\sigma_{\theta y}$, σ_{ry} TANGENTIAL AND RADIAL STRESSES ALONG THE Oy AXIS
$\epsilon_{\theta x}$, ϵ_{rx} TANGENTIAL AND RADIAL STRAINS ALONG THE Ox AXIS
$\epsilon_{\theta y}$, ϵ_{ry} TANGENTIAL AND RADIAL STRAINS ALONG THE Oy AXIS
ϵ_θ, ϵ_r TANGENTIAL AND RADIAL STRAINS ALONG THE θr DIRECTION

Figure A1. Notation for a disk subjected to two concentrically opposite uniform radial loads

At the center, r/R is equal to zero; thus, $\sigma_{\theta y}$, σ_{ry}, $\sigma_{\theta x}$, and σ_{rx} may be reduced to

$$\sigma_{\theta y} = \sigma_{rx} = \frac{2p}{\pi}\left[\frac{\sin 2\alpha}{2(1 - \cos 2\alpha)} - \frac{\pi}{4}\tan\alpha\right] \tag{A6}$$

$$\sigma_{\theta x} = \sigma_{ry} = -\frac{2p}{\pi}\left[\frac{\sin 2\alpha}{2(1 + \cos 2\alpha)} + \frac{\pi}{4}\tan\alpha\right] \tag{A7}$$

If α is very small (i.e., $\alpha < 7$ deg), then

$$\sigma_{\theta y} = \sigma_{rx} = \frac{2p\alpha}{\pi} \tag{A8}$$

$$\sigma_{\theta x} = \sigma_{ry} = -\frac{6p\alpha}{\pi} \tag{A9}$$

Equation A8 is used to determine the tensile strength of the material.

A.2 Elastic Parameters Analysis in Circular Disk

The modulus of elasticity E and Poisson's ratio ν at any point in an elastic medium can be determined readily as long as the principal stresses and the corresponding strains are known for that point. For an elastic disk, the principal stresses can be calculated from previous formulas, and the principal strain may be measured at least at the center. However, for soft materials such as soils, the measurement of strain is very difficult if not impossible; consequently, the elastic parameters cannot be accurately determined. An alternative method for measuring the elastic parameters was developed by Hadley et al.[18] in which E and ν were calculated from the measurement of deformations rather than strains.

Their mathematical derivation is based on the assumption that the material is homogeneous and isotropic and obeys Hooke's Law. Thus, for the plane stress case, the total deformations along the vertical and horizontal diameters of the disk are

$$v = \int_{-r}^{r} \varepsilon_y dr = \frac{1}{E} \int_{-r}^{r} (\sigma_{ry} - \nu\sigma_{\theta y})\, dr = \frac{1}{E} \int_{-r}^{r} \sigma_{ry} dr - \nu \int_{-r}^{r} \sigma_{\theta y} dr \qquad (A10)$$

and

$$u = \int_{-r}^{r} \varepsilon_x dr = \frac{1}{E} \int_{-r}^{r} (\sigma_{rx} - \nu\sigma_{\theta x})\, dr = \frac{1}{E} \int_{-r}^{r} \sigma_{rx} dr - \nu \int_{-r}^{r} \sigma_{\theta x} dr \qquad (A11)$$

where

v, ε_y = total deformation and strain, respectively, along the y axis

u, ε_x = total deformation and strain, respectively, along the x axis

Solving Equations A10 and A11 simultaneously, the value of Poisson's ratio can be expressed as

$$\nu = \frac{u \int_{-r}^{r} \sigma_{ry} dr - v \int_{-r}^{r} \sigma_{rx} dr}{u \int_{-r}^{r} \sigma_{\theta y} dr - v \int_{-r}^{r} \sigma_{\theta x} dr} \qquad (A12)$$

Given ν, the value of E can be obtained using Hooke's Law as follows. Along the x axis,

$$E = \frac{1}{u} \int_{-r}^{r} (\sigma_{rx} - \nu\sigma_{\theta x})\, dr \qquad (A13)$$

and along the y axis,

$$E = \frac{1}{v} \int_{-r}^{r} (\sigma_{ry} - \nu\sigma_{\theta y})\, dr \qquad (A14)$$

A computer program was used for performing the numerical integration for calculating ν and E.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Oldham, Jessie C
The influence of polymers on the engineering properties of cement-stabilized soil / by Jessie C. Oldham. Vicksburg, Miss. : U. S. Waterways Experiment Station, 1977.
viii, 43 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-77-14)
Prepared for Assistant Secretary of the Army (R&D), Department of the Army, Washington, D. C., under Project No. 4A161101A91D.
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